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Development of a Dynamic Biomechanical Model for Load Carriage: Phase IV Part C3:

Dynamic Assessment of Pressure Measurement Systems for use in Human Load Carriage

by

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Abstract

Soldiers, who transport equipment by foot, experience dynamic pressures as a result of personal load carriage equipment. To understand how these dynamic pressures affect soldier tolerance and performance, pressure measurement equipment must be able to accurately and repeatable measure changing applied pressures to the skin. Two modern pressure measurement systems with potential for application on human subjects were examined in this study: a piezoresistive technology by Vista Medical, Ltd., and a capacitance system by XSENSOR® Technology Corporation. Each system was tested to determine the accuracy and repeatability to highly controlled, standardized dynamic loading. To examine pressure sensor performance, each pressure sensor was cyclically loaded by an Instron 5500 R using a standardized protocol in each sensor's calibration range. Results showed the XSENSOR® had showed better accuracy compared to the FSA, since the XSENSOR® measured a force that was 64% of the peak force applied to the sensor; whereas the. FSA measure a force that was 49% of the actual applied force. Further, the XSENSOR® showed better repeatability for peak forces (1.3% coefficient of variation) compared to the FSA (20.8% coefficient of variation). Results suggest that both systems have poor accuracy in comparison to the Instron; however, the low coefficient of variation for the XSENSOR® means that an algorithm could be built to correct for the slow response time of the system. Further research is required to improve the accuracy and repeatability of the XSENSOR® for dynamic research applications.

Résumé

Les soldats qui transportent de l'équipement à pied subissent des pressions dynamiques causées par l'équipement de transport de charge personnel. Pour comprendre comment ces pressions dynamiques influent sur la tolérance et le rendement des soldats, l'équipement de mesure de pression doit pouvoir mesurer avec justesse et de façon répétable les pressions variables appliquées sur la peau. Deux systèmes de mesure ayant du potentiel d'utilisation sur des sujets humains ont été examinés dans le cadre de cette étude : un système piézorésistif fabriqué par Vista Medical Ltd. et un système capacitif fabriqué par Xsensor Technology Corporation. Chaque système a été mis à l'essai pour déterminer la justesse et la répétabilité des mesures sous une charge dynamique normalisée strictement contrôlée. Pour examiner les performances des capteurs de pression, chaque capteur a été soumis à une charge cyclique au moyen d'un Instron 5500 R à l'aide d'un protocole normalisé respectant la gamme d'étalonnage du capteur. Les résultats montraient que le Xsensor avait une meilleure justesse comparativement à celle du FSA, car le Xsensor indiquait une force égale à 64 % de la force maximale appliquée, tandis que le FSA indiquait une force égale à 49 % de la force réelle appliquée. De plus, le Xsensor présentait une meilleure répétabilité pour les forces maximales (coefficient de variation de 1,3 %) comparativement au FSA (coefficient de variation de 20,8 %). Les résultats semblent indiquer que les deux systèmes ont une mauvaise justesse comparativement à l'Instron; cependant, le faible coefficient de variation du Xsensor veut dire qu'on pourrait élaborer un algorithme pour corriger le long temps de réponse du système. Il faut des recherches plus poussées pour améliorer la justesse et la répétabilité du Xsensor pour les applications en recherche dynamique.

Executive Summary

To understand how soldiers experience dynamic pressures as a result of their personal load carriage system, pressure measurement tools must be able to accurately and repeatability measure changing dynamic pressures. Advances in modern technology have led to the development of a piezoresistive technology by Vista Medical, Ltd., and a capacitance system by XSENSOR® Technology Corporation, which may have potential for dynamic research on human subjects. The goal of this study was to examine the accuracy and repeatability of each system during highly controlled, standardized cyclic loading conditions.

Methods

A 3 mm Bocklite ® cushion was placed over the base plate of an Instron 5500 R. The pressure measurement pad was placed over the Bocklite ® to cushion the sensor. Each system was programmed to collect the maximal number of samples per second. For the FSA, the maximal sample rate for the pad tested was 12 Hz. For the XSENSOR®, the maximal sample rate for the pad was 30 Hz. The top of the Instron was mounted with a flat, circular metal attachment with a circumference of 7.4cm. This circular plate was attached to the Instron with a universal joint to allow the metal to apply an even load to each sensor pad. The Instron was then programmed to load each sensor pad with 10 cycles between 10 N and 90 N as fast as possible, while remaining within the sensor's calibration range. To maintain cyclic loading the calibration range for the FSA, the Instron was programmed to load the sensor at a rate of 90 N/s. To remain in the calibration range for the XSENSOR®, the Instron was programmed to load the sensor at a rate of 65 N/s. A trigger was used by Instron to match the timing of the applied loads from the Instron with samples collected by the pressure system. Means, standard deviations, and coefficient of variance were calculated for each system.

Results and Discussion

Results showed neither sensor had an acceptable level of accuracy. In comparison to the Instron, the current gold standard, the XSENSOR® measured a force that was 64% of the actual force applied maximal force by the Instron, compared to the FSA which measured a maximal force that was 49% of the actual applied force. Further, the FSA showed considerable 20% variation in error (ranging from 55% to 75%) which was noticeably larger than the 2% range of error found for the XSENSOR® (48% to 50% error). The combination of greater accuracy and smaller variation in error suggests that the XSENSOR® would be the most suitable pressure systems to development for dynamic human testing.

For repeatability, results showed that XSENSOR® had better repeatability for peak loads than the FSA, with a coefficient of variation of 1.3% and 20.8% for the XSENSOR® and FSA, respectively. When measured data from each cyclic load were compared for repeatability, results showed that the XSENSOR® had better repeatability for multiple standardized dynamic loads, given that the XSENSOR® had a coefficient of variance of 0.036 and the FSA had a coefficient of variance of 0.051. These results suggested that XSENSOR® may be more suitable for dynamic application than the FSA, if corrected for amplitude.

Conclusions

Results from this study suggest that the XSENSOR® has better potential for dynamic use on human soldiers, although more testing is required to develop software algorithms, improve hardware calibration methods and to improve software calibration methods in order to improved repeatability and accuracy during short duration loading applications on curved surfaces.

Sommaire

Pour comprendre comment l'organisme des soldats réagit aux pressions dynamiques causées par leur système de transport de charge personnel, les outils de mesure de pression doivent pouvoir mesurer avec justesse et de façon répétable les pressions dynamiques variables. Les progrès de la technologie moderne ont mené au développement d'un système piézorésistif par Vista Medical Ltd. et d'un système capacitif par Xsensor Technology Corporation, qui peuvent avoir du potentiel pour la recherche dynamique sur des sujets humains. Cette étude avait pour objectif d'examiner la justesse et la répétabilité des mesures de chaque système dans des conditions de charge cyclique normalisées strictement contrôlées.

Méthodes

Un matelas Bocklite® de 3 mm a été placé sur la plaque de base d'un Instron 5500 R. Le tampon de mesure de pression a été placé sur le matelas Bocklite® pour protéger le capteur. Chaque système a été programmé pour collecter le nombre maximal d'échantillons par seconde. Dans le cas du FSA, le taux d'échantillonnage maximal pour le tampon à l'essai était de 12 Hz. Dans le cas du Xsensor, le taux d'échantillonnage maximal pour le tampon à l'essai était de 30 Hz. Le haut de l'Instron était équipé d'une plaque métallique circulaire plate ayant une circonférence de 7,4 cm. Cette plaque circulaire était attachée à l'Instron au moyen d'un cardan pour permettre à la plaque d'appliquer une charge uniforme sur chaque tampon capteur. Ensuite, l'Instron a été programmé pour charger chaque tampon capteur au moyen de 10 cycles compris entre 10 N et 90 N le plus rapidement possible, tout en respectant la gamme d'étalonnage des capteurs. Pour maintenir la charge cyclique dans la gamme d'étalonnage du FSA, l'Instron a été programmé pour charger le capteur au taux de 90 N/s. Pour respecter la gamme d'étalonnage du Xsensor, l'Instron a été programmé pour charger le capteur au taux de 65 N/s. Un déclencheur a été utilisé par l'Instron pour synchroniser les charges appliquées par l'Instron avec les échantillons collectés par le système de mesure de pression. On a calculé les moyennes, les écarts-types et le coefficient de variation de chaque système.

Résultats et discussion

Les résultats indiquaient que ni l'un ni l'autre capteur n'avaient un niveau de justesse acceptable. Comparativement à l'Instron, la norme d'excellence actuelle, le Xsensor a mesuré une force égale à 64 % de la force réelle maximale appliquée par l'Instron, tandis que le FSA a mesuré une force maximale égale à 49 % de la force réelle appliquée. De plus, le FSA présentait une variation d'erreur de 20 % (erreurs comprises entre 55 % et 75 %) qui était nettement supérieure à la variation d'erreur de 2 % du Xsensor (erreurs comprises entre 48 % et 50 %). La combinaison de la justesse supérieure et de la variation d'erreur inférieure semble indiquer que le Xsensor serait le système de mesure de pression convenant le mieux à l'élaboration d'essais dynamiques sur des sujets humains.

Quant à la répétabilité, les résultats indiquaient que le Xsensor avait une meilleure répétabilité pour les charges maximales que le FSA, avec des coefficients de variation de 1,3 % et de 20,8 %, respectivement. Les résultats de la comparaison des données mesurées de chaque

charge cyclique aux fins de la répétabilité indiquaient que le Xsensor avait une meilleure répétabilité pour de multiples charges dynamiques normalisées : le Xsensor avait un coefficient de variation de 0,036, et le FSA, un coefficient de variation de 0,051. Ces résultats semblent indiquer que le Xsensor peut convenir mieux à une application dynamique que le FSA, sous réserve d'une correction de l'amplitude.

Conclusions

Les résultats de cette étude semblent indiquer que le Xsensor a un meilleur potentiel d'application dynamique sur les soldats, mais il faut d'autres essais pour élaborer des algorithmes logiciels, améliorer les méthodes d'étalonnage du matériel et améliorer les méthodes d'étalonnage du logiciel en vue d'améliorer la répétabilité et la justesse dans le cas des applications de charges de courte durée sur des surfaces incurvées.

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1.0 Introduction

Recently, clinicians and researchers have become increasingly interested in measuring the effects of a changing force applied to an area of human skin. A varying force, applied to a given area, creates a dynamic pressure on the skin. When repetition, duration and/or level of pressure applied are too great, tissue damage may occur. Pressure sensing technology has been used to evaluate the effects of dynamic pressure application on the skin, particularly to evaluate lower limb gait pathologies or other dynamic prosthetics and orthotic applications. However, well-controlled, scientific research investigating the ability of modern pressure-sensing technology to measure dynamic pressures in a valid, accurate, and repeatable manner have been understudied. There are a number of commercially available pressure measurement systems which are based on different technologies. The more popular technologies used include a resistive ink technology by Tekscan, Inc., a capacitance-based technology by Novel, Inc., and XSENSOR® Technology Inc., and a piezoresistive technology by Vista Medical, Inc. Previous DRDC reports have investigated these systems under loaded static conditions on curved and flat surfaces (Fergenbaum et al., 2003; Morin et al., 2003). This report will investigate the dynamic performance of the capacitance technology by XSENSOR®, Inc., and the FSA piezoresistive technology by Vista Medical, Inc.; two systems with limited information available in the literature.

2.0 Purpose

Based on the extremely limited research on the FSA and XSENSOR® measurement systems, and the lack of proper validation studies in the literature, the purpose of this study was to test the accuracy and repeatability of the FSA and XSENSOR® systems under highly controlled, dynamic mechanical loading conditions using a standardized protocol.

3.0 Review of Literature

There is a tendency to market pressure devices before they are ready for accurate clinical use and some users accept manufacturer's claims without question (Cavanagh et al., 1992). Although pressure systems may be used to study dynamic loads, there are no published studies which examine the dynamic performance of the FSA and XSENSOR® technologies, although some studies have examined the more commercially popular F-scan system. A recent DRDC report (Morin et al., 2003) investigated the accuracy, repeatability, creep and low threshold sensitivity of the FSA, the F-scan and XSENSOR® systems under standardized static loading on flat surfaces (Morin et al., 2003). Due to advances in pressure sensing technology, the XSENSOR® was reported to be more accurate and sensitive at low thresholds than the FSA and F-scan system under controlled static, flat loaded conditions. As a result of these findings, recent experiments

were conducted to compare the accuracy and repeatability of the XSENSOR® and F-scan on static curved surfaces which modelled a human soldier's hip and waist (Fergenbaum et al. 2003). Results showed the XSENSOR® was superior for accuracy on curved surfaces as well. The response of these systems under dynamic conditions has not been investigated to date.

Use of pressure measurement systems to study dynamic conditions has a number of advantages. First, a significant advantage is that these pressure systems are more portable than a traditional force plate, so gait can be studied more easily in field environments, such as during hill or stair climbing. Second, pressure data can be collected without the problem of requiring the subjects to alter stepping patterns to ensure subjects make contact with a fixed force plate (McPoil et al., 1995). Investigations into some commercial systems such as the F-scan, have been shown to be valid when compared to the force plate; however, the validity of the FSA and XSENSOR® requires further investigation.

The validity of the F-scan for dynamic use has been examined by a number of researchers. For example, Gorton et al (1996) compared the validity of the F-Scan insole system by comparing the F-scan output against the ground reaction forces collected from a force platform for walking subjects. Gorton et al. (1996) reported mean percent errors between 10 – 20% depending on weight of the subjects test (lighter subjects had greater errors). Similarly, Bauman et al (1992) reported differences in ground reaction forces between a force plate and the F-Scan system to be 10%. In similar studies, Mueller et al., (1994) reported a 13% error for ground reaction forces, during walking trials and Sumiya et al (1998) reported a 1-17% error during gait, when comparing the F-scan to a force plate. The results by Sumiya et al (1998), however, should be interpreted cautiously since the F-scan system tested was calibrated for pressures between 300-3000 kPa, yet the system was tested using peak pressure values between approximately 10-80 kPa. In the only published study on the validity for the FSA system, Jeffcott et al (1999) concluded that the FSA would be a valid tool to accurately measure pressure from horse saddles placed on a horses' back. Their results were inconclusive, however, since they could not prove validity nor accuracy because they had no way to calculate the actual pressure on the horses back given that they did not know the area of the saddle applying the force to the horses. For the XSENSOR®, no published on accuracy scientific studies could be found in the literature.

In the published literature, only a few pressure systems have been examined for repeatability for dynamic use. For the FSA system, a short abstract by Ferguson-Pell and Cardi (1991) compared the repeatability, accuracy and a number of other characteristics for systems between a VERG Force Sensing array (FSA system by Vista Medical Inc), a pneumatic pressure sensor (Talley Pressure Monitor 3), and a Tekscan 'seat' 2056 sensor array. The abstract, however, neglected to publish values for reproducibility and accuracy; only reporting that the Tally system was most reproducible and accurate. A preliminary study of the FSA system by Jeffcott et al. (1999), reported that the FSA system was repeatability in their study of pressures of horse saddles on static and moving horses. However, the authors made this conclusion using Pearson product-moment correlations between total saddle pressure and horse rider mass, rather than analyzing the correlations between any of the 5 test-retest conditions. The results of this report may also be skewed given that the authors admitted including data from sensors that were topped-out as a result of heavier riders (>300mmHg).

Published literature on the reliability of the XSENSOR® capacitance system has yet to be examined, although another capacitance system by Novel Inc., known as the EMED Pedar insoles, has been examined for reliability during dynamic testing and compared to the F-scan. McPoil et al (1995) found intraclass correlation coefficients for EMED Pedar insoles in range from 0.82-0.99, suggesting good reliability. The reliability of the F-scan was very poor in this study, given that intraclass correlation coefficients could not be calculated for the second peak produced during the stance phase of gait, since the between-trial variance was larger than the between-subject variance. In contrast, a study by Mueller et al., (1994) compared the validity and reliability of the F-scan during walking trials and reported a very high intraclass correlation (>0.94) between test occasions suggesting good repeatability for the F-scan. Given the conflicting results and confounding factors in the current literature during dynamic testing, it is clear that more highly controlled dynamic studies are required to determine the true reliability of current pressure technology.

McPoil et al (1995) identified a number of challenges that may affect the quality of dynamic test results in the literature. Some problems include: differences in gait patterns between different individuals; differences between gait patterns from trial-to-trial within an individual; susceptibility for mechanical breakdown of sensor pads from bending or stretching of transducers during testing; direct damage to sensor transducers as a result of excessive loading; and hot, humid and contoured environments (ie. foot) can affect sensor performance (McPoil et al., 1995). Therefore, it is obvious that highly controlled mechanical dynamic testing needs to be conducted to better understand the true capabilities of modern pressure measurement systems.

4.0 Methods

Two different pressure sensing systems were tested, a capacitance system and a piezoresistive system. The capacitance technology tested was the X2 seat system, manufactured by XSENSOR® Technology Corporation. The pad was constructed of a non-trim, flexible urethane plastic which was pliable and detachable from the electronics. The sensor pad model tested was an X36 pad referring to a 36 by 36 sensor arrangement, measuring 45.72 cm by 45.72 cm with a pad thickness of less than 1 mm. The sensor pad was composed of 1296 individual capacitive sensors and the system was capable of scanning all 1296 sensors on the pad at 30 scans per second using the smart media card and serial port for maximal sampling rate. The recommended pressure range was between 1.33-26.66 kPa (10-200 mmHg). The system was newly calibrated by the manufacturer since a calibration device is not currently available for purchase. The system also came with software calibration files created by the manufacturer.

The piezoresistive technology tested was the medical seat UT model, manufactured by Vista Medical Limited. The pressure pad was made of a thin (0.36 mm thick) fabric covered with an elastic top layer, measuring 53.34 cm by 53.34 cm in a 16 by 16 cm sensor array. Each pad had 256 piezoresistive sensors which were scanned 12 times per second. The system was sold with a laptop computer and associated software (currently version 3.1). The manufacturer recommended testing this seat pad for pressures in the range of 0 - 26.66 kPa (0 – 200 mmHg).

The system used was newly calibrated by the manufacturer who created software calibration files. A calibration kit was also available for purchase with the system.

The testing protocol involved the use of a dynamic testing device called the Instron 5500R. The Instron is a test device designed to evaluate the mechanical properties of materials. The Instron 5500R provides a wide range of testing solutions for verifying tension, compression, flexure, peel, tear and friction properties for a variety of materials. The Instron used a Merlin software fully integrated modular software package. The software was programmed to administer a preload value of 20 N at 90 N/s for 5 seconds before executing the cycling program. To start the cycling program the Instron software was programmed to create a sudden drop in applied force from 20 N to 10 N at 90 N/s, which was used at the beginning of each sampling period to align the Instron data with the data from the pressure systems. After this drop in load, the Instron executed the cycling program by applying 10 cyclic loads between 10 N and 90 N. To maintain loading in the calibration range for each pressure sensing system, the Instron cycling program was set to load the sensors at 90 N/s and 65 N/S for the FSA and XSENSOR®, respectively.

The loading rates and loads were selected to stay within the manufacturers specifications for pressure up to 26.67 kPa. To adhere to these recommendations, the maximal applied load by the Instron (90 N) was compared to the calibration range of the pressure system by calculating the maximal applied pressure by the Instron's circular attachment (radius=3.7 cm). This was done by dividing the Instron's maximal applied load (90 N) by the contact area of the circular attachment, using the equation of circle (area of a circle = $\pi \times r^2$). Further, to ensure that each sensel was maximally loaded, the sensor pad was manually aligned in the Instron with the aid of the pressure sensing software, to ensure that the orientation of the pressure pad was in a manner that would allow the Instron to apply maximal contact area to each individual sensel.

A 3 mm Bocklite ® cushion was placed over the base plate of the Instron. The pressure measurement pads were placed over the Bocklite ® as seen in Figure 1. Each pressure system was programmed to collect the maximal number of samples per second. For the FSA, the maximal sample rate for the pad tested was 12 Hz. For the XSENSOR®, the maximal sample rate for the pad was 30 Hz. The top of the Instron was mounted with a circular metal plate that was 7.4 cm in circumference and applied an even load to each sensor pad because of a universal joint connecting the circular metal plate to the Instron.

For data analysis, the first and the last cycles collected by the pressure system were removed so that only steady state data were analyzed as recommended by Cavanagh et al. (1992) for dynamic studies of gait. For statistical analysis, all protocols were analyzed using MS Office XP software in an Excel® spreadsheet. Data from loading trials were normalized by converting measured pressures from the pressure system (in mmHg) into force (in Newtons) for graphing purposes. Then the measured force was divided by the actual force (in Newtons) applied by the Instron, to allow for comparison between FSA and XSENSOR® performance. The mean, standard deviation and coefficient of variance were also calculated for cyclic loading trials using an MS Office XP spreadsheet.

Figure 1: Set up for the XSENSOR® Pressure Pad in the Instron.

5.0 Results

Figure 2 compares the performance of the FSA pressure system when eight cyclic loads were applied by the Instron at 90 N/s while remaining within the system's calibrated range of 0-26.66 kPa (0-200mmHg). The FSA showed relative consistency in the shape of the loading profile but was only 36% of the actual signal size. Figure 3 compares the performance of the XSENSOR® pressure system when eight cyclic loads were applied by the Instron at 65 N/s while remaining within the system's calibrated range of 1.33 – 26.66 kPa (10-200mmHg). In this sample, the XSENSOR® showed a similar profile to the Instron, but a changing lag time and amplitude of only 51% of the actual signal size. In comparing the maximal force applied to each sensor pad by the Instron to the maximal force reported by the pressure measurement system (Table 1), the coefficients of variation show greater consistency in peak values for XSENSOR® (coefficient of variance=0.013) than for the FSA (coefficient of variance=0.208). Table 2 compares the average force from all eight loading trials administered by the Instron (all loads combined) to the average force reported by the pressure measurement system for all loads. The sampling rate was adjusted to the maximum sampling rate of the FSA system. Results confirm that neither system matches the Instron's force output and that coefficients of variation are dramatically different for the FSA.

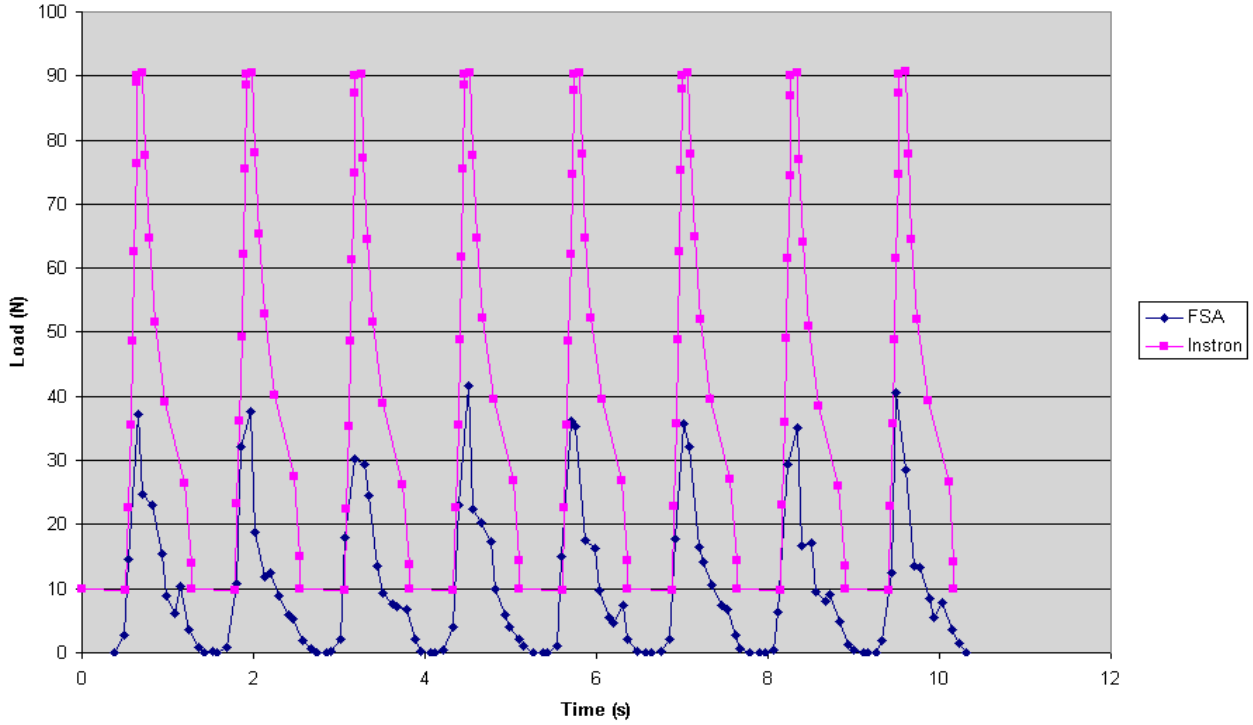

Figure 2: Cyclic Loading Results for the FSA System.

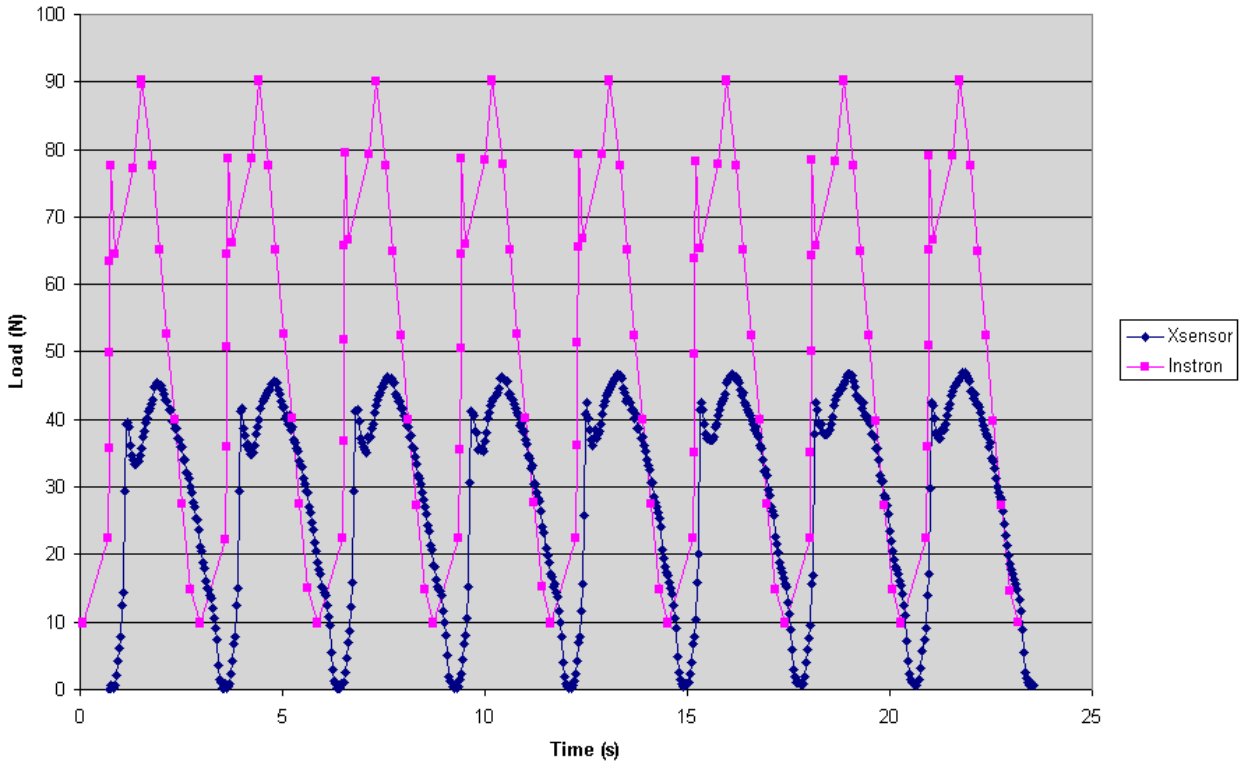

Figure 3: Cyclic Loading Results for the XSENSOR® System.

Table 1 – Comparison of Normalized Maximal Peak Values between Instron, FSA and XSENSOR®.

Peak	FSA Measured Force (N)	Instron Measured Force (N)	Normalized*	XSENSOR® Measured Force (N)	Measured Force (N)	Normalized*
1	23.05	90.46	0.25	45.20	90.26	0.50
2	37.64	90.56	0.42	45.58	90.22	0.51
3	30.14	90.30	0.33	46.36	90.13	0.51
4	22.46	90.48	0.25	46.30	90.23	0.51
5	36.25	90.55	0.40	46.70	90.23	0.52
6	35.76	90.45	0.40	46.69	90.18	0.52
7	35.07	90.40	0.39	46.79	90.21	0.52
8	40.64	90.67	0.45	46.92	90.24	0.52
Average	32.63 ± 6.8	90.48 ± 0.11	0.36 ± 0.074	46.32 ± 0.62	90.21 ± 0.041	0.51 ± 0.0069
Coefficient of Variance	0.208	0.00122	-	0.0134	0.000454	-

***** This normalized value was calculated my dividing the measured force from the pressure system by the actual force administered by the Instron.

Table 2 – Comparison of cycles for the repeatability of each system.

Cycle	FSA	XSENSOR®
1	10.57	26.31
2	10.50	28.52
3	10.05	28.29
4	10.14	28.45
5	10.75	29.85
6	9.78	28.22
7	9.21	29.60
8	10.57	29.28
Mean of all Cycles	10.20	28.56
Standard Deviation	± 0.52	± 1.03
Coefficient of Variance	0.051	0.036

6.0 Discussion

For the dynamic testing in this study, validity refers to the sensor system's ability to measure the actual forces that were applied to the pressure pad by the Instron. Normalized data in Table 1 shows that the FSA considerably underestimated actual applied loads (accuracy error) compared to the XSENSOR®, given that the XSENSOR® measured a peak force at a valued that was 64% ± 7% of the actual applied load, compared to the FSA which measured a peak force that was 49% ± 1% of the actual load. The 64% accuracy error for the calibrated FSA system was dramatically different than Jeffcott et al. (1999) who reported repeatability and accuracy levels to

be ± 5% for the FSA in a preliminary study using horse saddles. Further, normalized data in Table 1 also showed considerable variation in range of errors, ranging from 55% to 75%, which was a noticeably larger range of error than for the XSENSOR® (48% to 50% error). The FSA is also limited for dynamic testing since the sampling speed is 40% slower than the XSENSOR® and is better suited for static situations. Considering the magnitude of accuracy error and the variability of accuracy error, the data in this study suggested that the XSENSOR® would be better candidate for future study, if corrections were to be developed to improve accuracy.

Although controlled, dynamic testing for the FSA and XSENSOR® have not been published in the scientific literature, there is literature on the validity of the F-scan pressure under dynamic conditions. To date, studies on human gait comparing the F-scan to GRF from a force plate have shown accuracy errors in the range of 10 to 20% (Gorton et al., 1996; Bauman et al., 1992; Mueller et al., 1994). Recently, however, it has been shown that faster gait speeds for both walking and running can result in increased error by underestimating actual loads by as much as 44% for a calibrated F-scan sensor (Sih, 2001). An Instron was used in this study to eliminate confounding factors such as differences in gait speed, however, it is clear that the 48% to 50% accuracy error found for the XSENSOR® system would need to corrected, perhaps though software changes, so that the accuracy could be improved to values closer to the F-scan system.

For reliability, the coefficient of variation (CV) was used to measure of the dispersion of data around the mean: an important measure of reliability. Smaller dispersion about the mean suggests greater reliability, since a smaller CV indicates that samples are more similar to one another. The Instron was programmed to apply a maximum force of 90 N of force and showed excellent reliability in producing this maximal force, since variation from this maximum was extremely small; less than 0.122% variation as shown in Table 1. The XSENSOR® system showed excellent reliability for sampling maximal force, demonstrating a minimal 1.34% variation about the mean (CV=0.0134). In contrast, the FSA showed the poor reliability, demonstrating a variation of 20.8% variation about the mean for mean maximal pressure collected (CV=0.208). These results are consistent with Jeffcott et al. (1999) who also reported considerable reliability problems with the FSA, even when dynamic conditions were controlled by using the same moving horse at the same speed. Based on their results Jeffcott et al. (1999) concluded that the FSA sensors may not be sensitive enough to study the dynamic motion of a horse. This result was confirmed in this studying that rates of 12 samples/s are not adequate for most human motions and would therefore contribute to a high coefficient of variability.

Although the coefficient of variation for the FSA and XSENSOR® systems have not been explored in the literature, some coefficient of variation data has been published for the F-scan system which could be useful for comparison. Ahroni et al. (1998) obtained coefficients of variation, ranging from 0.12 to 0.20 for most a number of gait measures when testing diabetic patients. Further, Ferguson-Pell (2000) reported coefficients of variance for linearity ranging from 1.9%-9.9% using a Flexiforce system; a low pressure detection sensor by Tekscan Inc. As well, Hadcock (2002) reported coefficients of variation for the F-scan between 0.10 and 1.03 for testing on a human-sized hip model. In comparison to Tekscan technology, the reliability of the XSENSOR® in this study under dynamic test conditions was excellent. In contrast, the current FSA system would require significant improvement to bring its dynamic reliability closer to the reliability of both the XSENSOR® and F-scan technology, since its large coefficient of variation

suggests that the FSA would not be adequate to consistently identifying a maximal dynamic pressure applied to the pad, even when that pressure is in the sensor's calibration range.

Given that pressure systems may be used to study a number of dynamic loads over time, this study compared the repeatability of the FSA and XSENSOR® by comparing the measured values from each cyclic load. Table 2 shows that the XSENSOR® had a coefficient of variance of 0.036 and the FSA had a coefficient of variance of 0.051 demonstrating that the XSENSOR® had better repeatability than the FSA. Given that that the XSENSOR® system shows less variation when dynamically loaded under highly controlled conditions, these data suggests that the XSENSOR® may be a more acceptable for use in dynamic human trials. Given the 20.8% coefficient of variation for peak loads (Table 1) and the 5.1% variation for the mean of all cyclic loads (Table 2), it is obvious that the current FSA UT seat model should not be used for dynamic applications in human study experiments. However, it could (if corrected for amplitude) be useful in static or quasi-static situations, such as seated or lying postures.

There are a number of explanations to explain the poor accuracy and inadequate reliability of the FSA system compared to the XSENSOR®. First, the FSA may have had more problems associated with the system for reasons related to its piezoelectric properties. Piezoelectric materials are generally known to have complex properties and piezoelectric sensors may cause different outputs as a result of stress in different directions (ie. shear), sensitivity to bending, and sensitivity to temperature changes (Cavanagh et al., 1992). Although these confounding factors were limited in this study, the manufacturer may not have made adequate compensations in the software to compensate for complex nature of the small piezoelectric sensors used for dynamic conditions.

Second, there are a number of calibration issues that may affect sensor performance. Many of the companies sell air bladders to calibrate sensors, although the relationship between values developed from air pressure to other surfaces or applications are unclear (Cavanagh et al., 1992). Differences in calibration and differences in response to loading on a material with compliance similar to human skin (Bocklite ®) could account for differences in pressure readings between the FSA and XSENSOR®.

Third, each sensor pad is made up of many individual sensors and each individual sensor is unique and may respond differently to an air bladder applying a uniform pressure across an entire sensor pad. Even though the software is used during the calibration procedure to equilibrate and compensate for differences (or errors) between individual sensors, inadequacies in software can also contribute to system inaccuracy and instability (Sih, 2001). An additional problem noted by Sih (2001) is that with dynamic testing, the load varies with time due to creep in the pressure values. Therefore, the ability to collect accurate dynamic results is compromised from the onset, since the FSA and XSENSOR® manufacturers currently employ static calibration procedures for all calibrations.

Last, many of the devices used for in-shoe measurements exhibit a non-linear relationship between pressure and voltage output, therefore manufacturers who simplify the calibration procedure by implying a linear behavior between will contribute to error (Cavanagh et al., 1992). In addition, Cavanagh et al. (1992) notes that, when only a single calibration constant is provided

for many transducers, the error becomes additive and is likely to be large. In this study, each manufacturer provided freshly calibrated pads in the 10-200 mmHg range; however, details of how the software calibrates each sensor are not currently available since each companies wants to protect their intellectual properties. Nonetheless, differences in how each company selects to compensate for the relationship between voltage output and pressure, could account for the differences in sensor performance collected during this study.

7.0 Conclusions

The combination of greater accuracy, smaller variation in accuracy error, and better repeatability, suggests that the XSENSOR® would be the most suitable pressure systems to development for human dynamic testing. A number of confounding factors would have to be corrected, however, before the system could be used dynamically. Improvements would have to be made to software to improve accuracy and repeatability over time, to develop hardware for dynamic calibrations procedures specifically to the capacitance sensors used, and to develop software algorithms to improve the accuracy of the software calibration files to reflect the actual, more complex relationship between pressure and voltage/current output.

8.0 Next Steps

Results from this study show that the XSENSOR® would be the best investment in terms of potential future dynamic research on soldiers. However, to use the XSENSOR® for dynamic research, further testing needs to be conducted using faster, more precise, more advanced dynamic equipment than the Instron 5500 R to gain a more comprehensive understanding of the XSENSOR® response to dynamic loads over time. When more information is known about the sensor's response to dynamic loads, new algorithms will need to be developed for the software to improve accuracy and repeatability. Further, a dynamic hardware calibration procedure must be developed to so that the system can accurately measure dynamic pressures with acceptable reliability.

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(U) Soldiers, who transport equipment by foot, experience dynamic pressures as a result of personal load carriage equipment. To understand how these dynamic pressures affect soldier tolerance and performance, pressure measurement equipment must be able to accurately and repeatable measure changing applied pressures to the skin. Two modern pressure measurement systems with potential for application on human subjects were examined in this study: a piezoresistive technology by Vista Medical, Ltd., and a capacitance system by XSENSOR® Technology Corporation. Each system was tested to determine the accuracy and repeatability to highly controlled, standardized dynamic loading. To examine pressure sensor performance, each pressure sensor was cyclically loaded by an Instron 5500 R using a standardized protocol in each sensor's calibration range. Results showed the XSENSOR® had showed better accuracy compared to the FSA, since the XSENSOR® measured a force that was 64% of the peak force applied to the sensor; whereas the. FSA measure a force that was 49% of the actual applied force. Further, the XSENSOR® showed better repeatability for peak forces (1.3% coefficient of variation) compared to the FSA (20.8% coefficient of variation). Results suggest that both systems have poor accuracy in comparison to the Instron; however, the low coefficient of variation for the XSENSOR® means that an algorithm could be built to correct for the slow response time of the system. Further research is required to improve the accuracy and repeatability of the XSENSOR® for dynamic research applications.

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(U) Load carriage; Dynamic Biomechanical Model; Pressure measurement systems; Dynamic Pressures; XSENSOR®; Skin Contact Pressures